HERO : High-Energy Replicated Optics for a Hard-X-Ray Balloon Payload

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ABSTRACT

We are developing high-energy grazing-incidence optics for a balloon-borne hard-x-ray telescope. When completed the instrument, termed *HERO* for High Energy Replicated Optics, will have 200 cm^2 effective collecting area at 40 keV and ≤ 30 arcsec angular resolution. The payload will offer unprecedented sensitivity in the hard-x-ray region, with milliCrab level sensitivity on a one-day balloon flight and 100 microCrab on an ultra-long-duration flight. While the full science payload is scheduled for flight in 2002, an engineering/proving flight is currently awaiting launch. This flight, consisting of just two mirror modules, each containing three nested shells above a pair of gas scintillation proportional counter focal plane detectors, is intended to test a newly designed gondola pointing and aspect system and to examine the stability of optical bench designs. This paper provides an overview of the HERO program.

Keywords: Hard x ray, optics, electroformed nickel replication

1. INTRODUCTION

Focusing optics have brought about spectacular advances in x-ray astronomy at low energies, but their application to higher energies awaits the development of suitable mirrors. Various groups have undertaken the development of multilayer-coated foil optics, where the multilayers give useful reflectivities at energies above the critical angle. In this paper, we report on an alternative approach using full-shell shallow-graze-angle iridium-coated replicated mirrors. The advantage of this approach is that complex coating procedures are avoided, and requirements for mirror surface quality are relaxed. An additional benefit is that the full shell replicated optics, used for example on the XMM-Newton mission[1], have so far demonstrated superior angular resolution over foil mirrors. This in turn translates directly into greater sensitivity through reduced focal spot size.

To demonstrate the viability of this approach, we initiated the High Energy Replicated Optic (*HERO*) program, detailed below. *HERO* will be a balloon-borne instrument capable of sub-milliCrab sensitivity and ≤ 30 arc sec angular resolution

2. BALLOON PAYLOAD

The full *HERO* balloon payload consists of 16 identical modules, each containing 15 nested mirrors. The mirrors are a conical approximation to a Wolter 1 geometry, with a monolithic shell structure containing both "P" and "H" segments. Each shell is fabricated from electroformed nickel, approximately 0.25 mm thick, and is coated inside with about 50 nm of sputtered Iridium. The innermost shell of each module has a diameter of 50 mm at its axial mid point and the outermost shell has a corresponding diameter of 94 mm. Metrology of early mandrels indicated a Half Power Diameter (HPD) of around 30 arc-sec and this was borne out by tests of replicated shells. Since then, we have slowly improved our mandrel fabrication process and now have a target HPD of 15 arc sec at 50 keV for each mirror module. Table 1 details the full *HERO* mirror configuration.

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Table 1: *HERO* balloon payload mirror configuration.

Mirror shells per module	15
Inner shell diameter	50 mm
Outer shell diameter	94 mm
Total shell length	610 mm
Focal length	6 m
Type	Conic approximation to Wolter 1
Fabrication process	Electroformed nickel replication
Shell thickness	0.25 mm
Coating	Sputtered iridium
Number of mirror modules	16
Effective area	~ 200 cm^2 at 40 keV, ~ 120 cm^2 at 60 keV
Angular resolution	15-30 arc sec to 60 keV
Field of View	5 arcmin FWHM at 60 keV

As focal plane detectors for early flights we have developed high-pressure gas scintillation proportional counters[2]. These provide good energy resolution (3% at 60 keV), but their spatial resolution, at 0.5 mm (60 keV), is not quite adequate to provide a factor of two over-sampling of a 15 arc sec mirror module at 6 m. We are therefore evaluating pixellated Cadmium-Zinc-Telluride detectors with 0.3 mm readout pitch for future focal plane use.

Long- and ultra-long-duration balloon flights provide excellent opportunities to realize the very high sensitivities afforded by even modest mirror collection areas. With 200 cm^2 effective area at 40 keV, and a detector backgrounds of 5.10^{-4} cm^{-2} s^{-1} keV^{-1}, we expect 300 microCrab sensitivy in a 10 day mission (10^5 s per target) and better than 100 microCrab in a 100 day flight (10^6 s per target). Even a standard 3-hour observation will approach 1 milliCrab, making over 100 galactic sources amenable to study. Contrast this to non-focusing systems, where a typical 1000 cm^2 detector would achieve at least an order of magnitude poorer sensitivity. Thus the *HERO* payload would be equivalent to 100 such detectors. Figure 1 shows the expected *HERO* sensitivity.

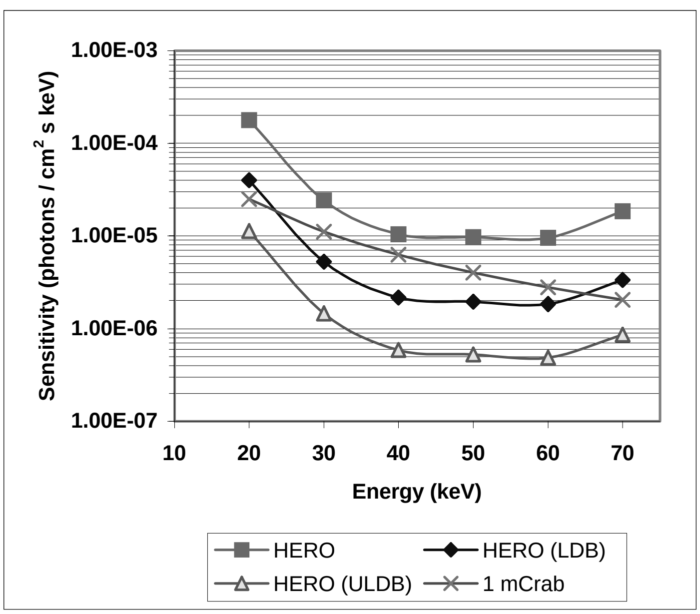


Figure 1: *HERO* balloon payload sensitivity (5σ) over 10 keV bands for 10^4s, 10^5s (LDB) and 10^6s (ULDB) observations. A float altitude of 40 km and a zenith angle of 30^o are assumed.

3. MIRROR FABRICATION

The HERO mirrors are fabricated using electroform-nickel replication off super-polished electroless-nickel-coated aluminum mandrels. This process, similar to that used to produce the nickel mirrors for the XMM mission, has been further developed at MSFC to satisfy future needs for high-resolution, light-weight optics. In particular, use is made of an ultra-high-strength glassy nickel alloy that has been developed to permit very-thin-walled large-diameter optics to be fabricated without process-induced plastic deformations which would distort the mirror figure.

The first step in the production chain is the fabrication of aluminum mandrels with radii approximately 0.1 mm below that required for each shell. The mandrel is then coated with 0.175 mm of electroless nickel (figure 2) to give a hard surface suitable for polishing and the mandrels are then accurately figured using cylindrical grinding machines. A mechanical super polish then takes place (figure 3), resulting in a surface of around 0.4 nm rms, which is sufficient to ensure that scattering does not dominate the mirrors performance up to the cut-off energy of each shell. Metrology is performed at MSFC at each step, using a horizontal long-trace profilometer for axial figure measurements (figure 4), a ZEISS co-ordinate axis machine for cone angle measurements, a PNEUMO for circularity, and a WYKO TOPO 2D for characterizing surface finish.

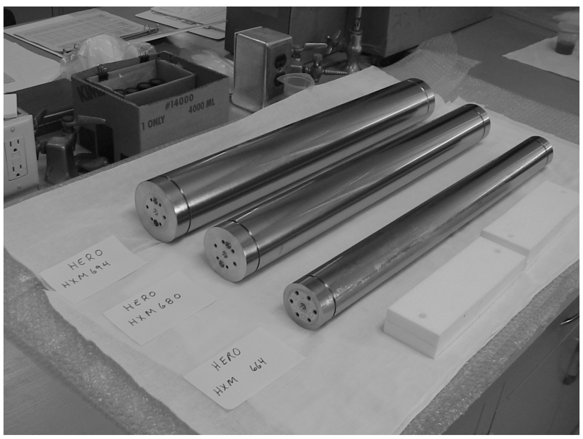


Figure 2. HERO mandrels after electroless-nickel plating.

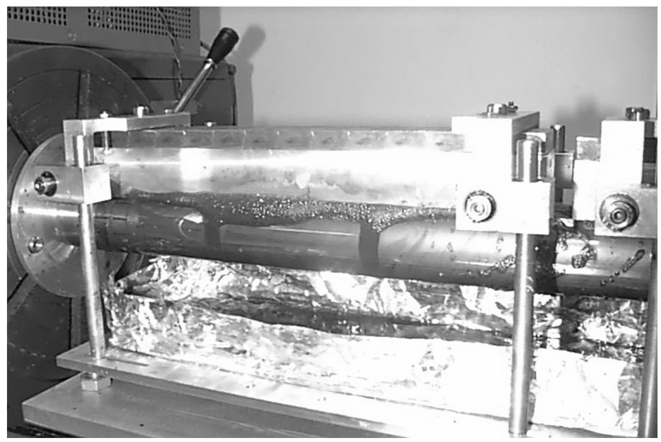


Figure 3. A 50-mm diameter mandrel being polished.

To prepare for electroforming, the surface of the mandrel is treated to form an oxide layer from which the shell can be easily released, and the mandrels are immersed in the plating tank. A typical 0.25-mm-thick shell takes approximately 1 day to electroform, at which time the mandrel is taken from the bath, rinsed and dried and then cooled to separate the shell from the mandrel. This is done simply by immersing the assembly into a dewar of liquid nitrogen and then sliding the mandrel from the shell when release takes place. The capillary action of the liquid, which provides a cushion between the mandrel and the released shell, and the hardness of the shell material (greater than 50 on the Rockwell C scale) ensure that the critical inner surface of the shell is not scratched during the process.

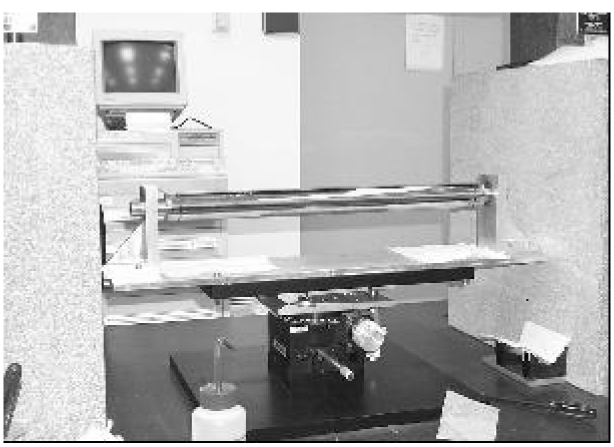


Figure 4. A HERO mandrel on the long trace profilometer.

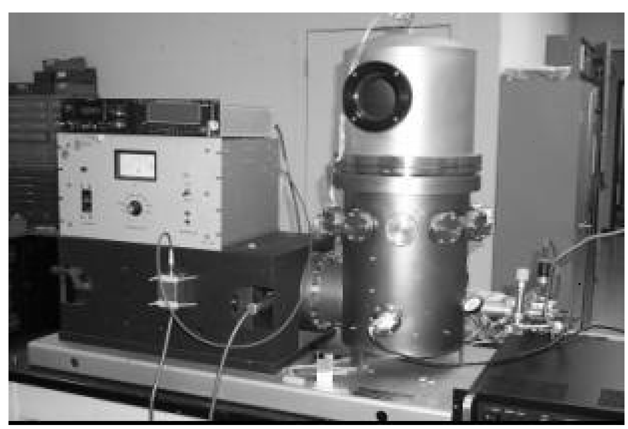


Figure 5. Iridium sputtering system.

After release and cleaning, to remove any residual plating solution or water stains, the shell is sent to the coating chamber where around 50 nm of near-bulk-density iridium is sputtered onto the inner optical surface (see Figure 5). The mirror shell is then ready for use.

While the electroformed replication process is capable of producing very good optics, a few-arc-sec half power diameter under optimum conditions, each shell necessitates the fabrication of a high-quality mandrel and these can prove very expensive in some cases. To keep expenses appropriate for a balloon program, we have used grinding rather than diamond turning and have worked with vendors to optimize the process to keep overall costs down. Table 2 details the evolution of this effort. Initial attempts at cylindrical grinding led to mandrels with poor surface finish and unacceptable figure accuracies which in turn led to 3 months of labor-intensive manual figure correction and polishing. This in turn drove up the cost of each mandrel. By refining the grinding process, the burden on the optician/polisher was reduced and the overall costs came down. The current process, still under evaluation, should reduce the per mandrel cost to around \$5k to \$6k, which means a total cost of only \$75k-\$80k for the full set of HERO mandrels.

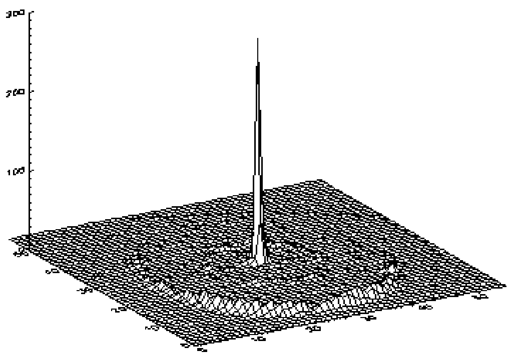
Table 2 : HERO Mandrel Costs as a Function of Time.

Turned Aluminum (\$k)	***Nickel (\$k)***	***Grinding Technique***	***Finish***	***Grinding (\$k)***	***Polishing (\$k)***	***Total Time (months)***	***Total Mandrel Cost (\$k)***
1.2	0.5	Cylindrical, single wheel	250 nm surface 1.5 μm figure	0.9	21 (3 months)	4	23.6
1.2	0.5	Cylindrical, 2 wheels, filtered coolant, steady rest	50-75 nm surface 0.75 μm figure	3.6	7.0 (1 month)	2	12.3
1.2	0.5	As above, but air bearing machine and diamond wheels (switch vendors)	20nm surface, < 0.5 μm figure	1.3	3.5 (0.5 month)	1.5	6.5

To date, the maximum number of replications from a single mandrel is four, during which time essentially no degradation of the mandrel surface was seen. Refurbishment in these cases was simply confined to re-cleaning the mandrel before the next use. It is, therefore, expected that the desired full 16 shells can be replicated from each mandrel with a minimum amount of re-polishing.

4. MIRROR TEST RESULTS

Early mirror tests confirmed that the replicated shells matched performance predictions based upon mandrel metrology. Figure 6 shows a surface contour plot of the response of a 50-mm diameter, 6-m focal length optic tested in the 102-m-long beam facility at MSFC. The image was taken using a gas-scintillation proportional counter. Figure 7 shows the energy response of the (iridium-coated) optic. The Half-Power-Diameter (HPD) of this particular shell was measured to be 30 arcsec up to the x-ray source imposed cut-off of 45 keV., consistent with a performance prediction of 28 arc sec made from metrology of the mandrel. This demonstrates that the replication process is faithfully reproducing the figure and surface of the mandrel.



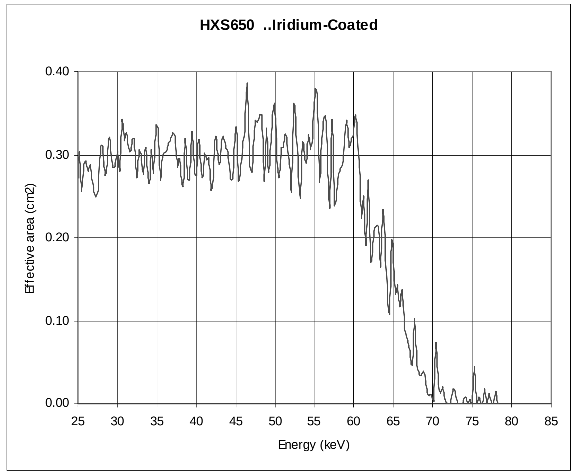
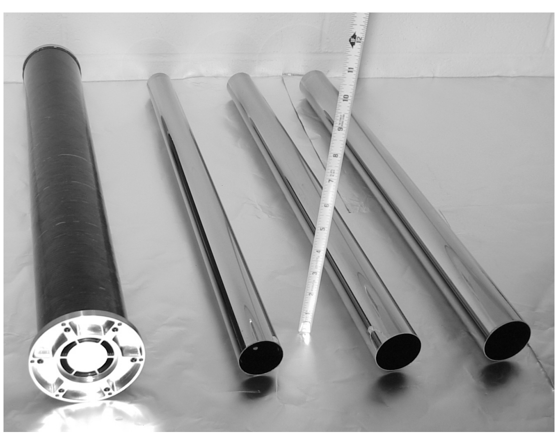


Figure 6. Surface contour plot of mirror response over an energy band from 25–35 keV.

Figure 7. Effective area vs energy for a 50-mm-diameter shell

As an intermediate step, to check out the mirror technology and supporting gondola subsystems we have made a series of special 3-m-focal length optics that are awaiting flight in Fort Sumner, New Mexico (see section 5.) These optics are arranged in two identical modules, each containing 3 nested 0.5-mm-thick mirror shells of intersection diameters 40, 44 and 48 mm. The mirrors are housed in carbon-fiber-composite tubes, wound to have a CTE matching that of the nickel, and are held at their ends with a stainless steel spider arrangement. Figure 8 shows one of the two modules with its three replicated optics. Figure 9 shows the measured on-axis mirror module response for a source at 102 m together with the measured flux contained within a 0.5-mm-diameter region. The half-power-diameter for the whole mirror assembly is around 45 arc sec and the total on-axis area for infinite source distance is 4 cm^2 (for 2 modules). While this is a very small collecting area it is more than adequate to provide images, in several energy bands, of bright galactic sources in a typical 1-day balloon flight.



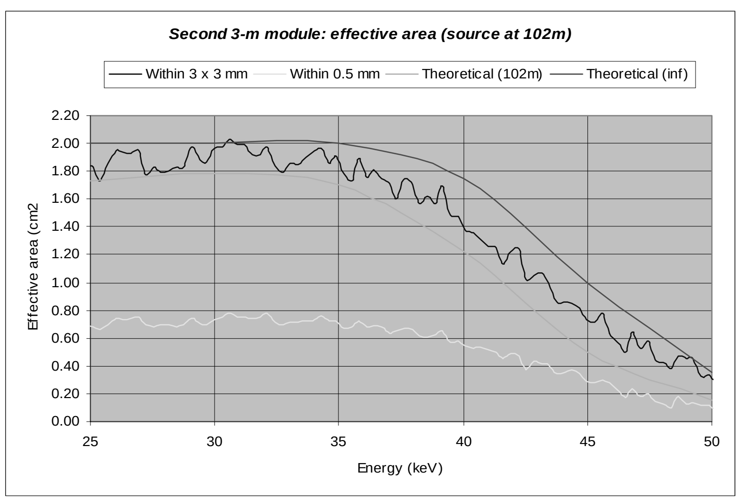


Figure 8. A 3-m-focal length flight mirror housing With its three replicated mirror shells.

Figure 9. Measured on-axis response of a flight mirror module.

The imaging performance of all shells fabricated to date is limited by axial slope errors in the mandrel fabrication process. It is anticipated that mandrels currently being figured by an improved grinding process will have superior figures that in turn will place less of a burden on the optician who must attempt to correct any errors through hand polishing. The goal for the HERO optics is a per-shell HPD of 15 arc seconds. The conic approximation to the Wolter-1 geometry imparts a maximum error of 10 arc sec (HPD) for the outermost HERO shell.

5. DEMONSTRATION FLIGHT

As a necessary first step, to demonstrate components of the technologies necessary to make the full HERO science payload a reality, we are flying a small 3-m-focal-length optical system consisting of a pair of mirror modules, each containing three nested nickel mirrors (figure 10). As focal plane detectors, a pair of gas scintillation proportional counters has been developed (figure 11). The mirrors and detectors are mounted on an optical bench, a light-weight truss system using graphite fiber tubes, with a tip/tilt mechanism that permits precise alignment of the optics with each other and with the star (aspect) camera. The heavily-baffled camera has been designed to perform daytime measurement of 7th magnitude and brighter stars to provide ~ 8 arc sec aspect knowledge around the clock. The data from this camera are fed back to the gondola control system to give an anticipated pointing stability of better than 30 arc sec. It is important to keep the x-ray source near the axis of the mirrors as the mirrors have a small field of view. At 40 keV, the mirror response drops to 50 % at 4 arc minutes off axis.

Figure 10. Two mirror modules mounted in the gondola alongside the star camera baffle tube.

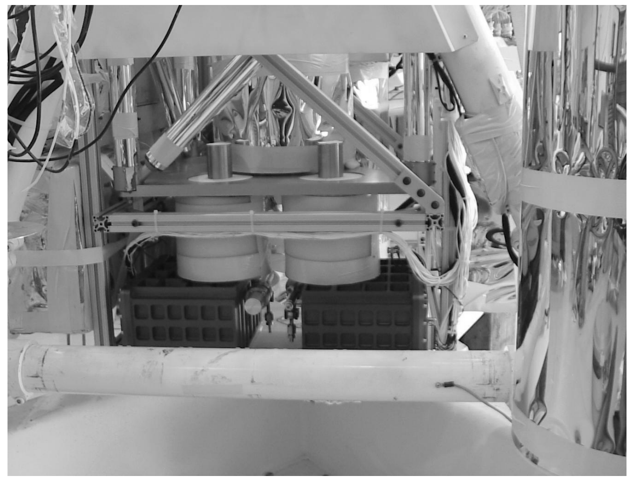


Figure 11. The two gas scintillation proportional counter focal plane detectors.

For pre-launch alignment we use a system of lasers which first project back from the gondola to define the location of an alignment fixture and then from the alignment fixture back through the x-ray optics and star camera (figure 12). By using diffuser screens on two of the lasers, to give a broad parallel beam on each of the two mirror modules, a series of focused rings is observed on the entrance window to each of the two focal plane detectors. Adjusting the mirror's tip/tilt mechanisms then permits fine adjustment of the alignment, as evidenced by the concentricity of the focused rings from single and double reflection off the mirrors surfaces (figure 13). In this manner the alignment of each optic to the star camera can be easily adjusted to better than 30 arc sec.

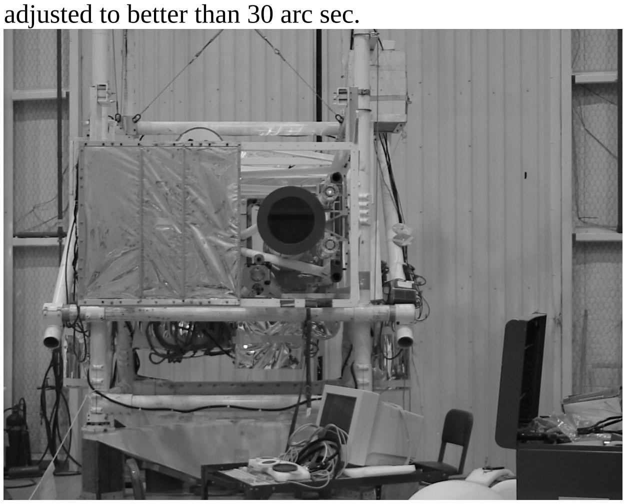


Figure 12. The replicated optic modules illuminated by lasers during the alignment process.

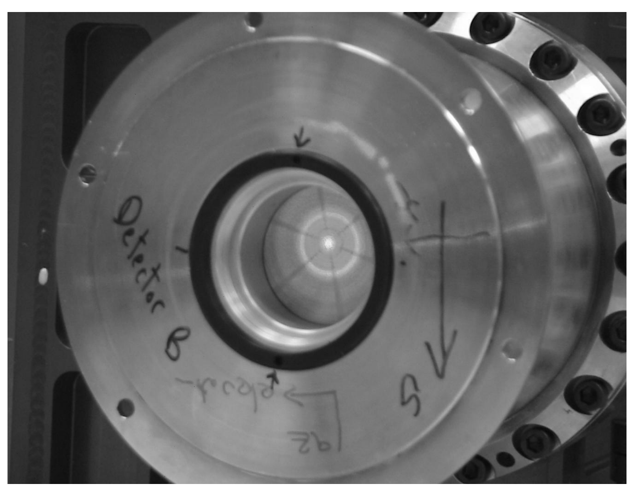


Figure 13. The reflected laser light on the detector when the mirror modules are correctly aligned.

This first flight will provide valuable information on many aspects of the HERO payload. It will confirm that the hard-x-ray optics can be successfully aligned and that the optical bench design provides adequate stability to maintain that alignment during the flight. It will demonstrate the performance of the pointing system and test the day/night aspect camera, and via this, confirm that x-ray images can be reconstructed using the attitude data. It will also, of course, give the first hard-x-ray focused images of bright galactic sources.

5. SCHEDULE

The first test flight of the proving 3-m system was scheduled for Spring 2000, but poor weather forced a cancellation. The payload is currently sitting in New Mexico awaiting a Fall 2000 flight. The full science payload, with 6-m optics, is scheduled for flight in 2002.

All 15 mandrels needed for the full HERO science payload are currently in fabrication, with 5 being ground to figure and the remainder being coated with electroless nickel. By the end of 2001, they are all scheduled to be completed, with the last shells following shortly thereafter. The current gondola will not handle the 6-m focal length and so it will be modified to increase its overall height while still maintaining all the existing mechanisms.

A final refinement to the HERO payload is being considered. While providing groundbreaking science in the hard-x-ray region, its iridium-coated optics have a high-energy cut-off at the iridium K edge (75 keV). With the recent observations of titanium-44 lines in the supernova remnant Cas-A, an important function of future hard-x-ray telescopes has become to search for these lines in other sources. The lines fall at 68 and 78 keV, and so, for the HERO payload to provide for high-sensitivity observations of these features, the response in this energy range must be increased. We are investigating the addition of several extra outer shells that would be coated with graded multilayers to provide the necessary high-energy coverage.

ACKNOWLEDGEMENTS

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